STATE OF ILLINOIS
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DIVISION OF THE
STATE GEOLOGICAL SURVEY
JOHN C. FRYE, *Chief*
URBANA

REPORT OF INVESTIGATIONS 178

METAMORPHISM OF COAL BY PERIDOTITE DIKES IN SOUTHERN ILLINOIS

BY

KENNETH E. CLEGG

PRINTED BY AUTHORITY OF THE STATE OF ILLINOIS

URBANA, ILLINOIS

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METAMORPHISM OF COAL BY PERIDOTITE DIKES IN SOUTHERN ILLINOIS

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ABSTRACT

Field and laboratory investigations were made of dikes and adjacent natural coke—metamorphosed bituminous coal—which were uncovered in a strip mine. Microscopic analysis showed the intruded material to be an ultra-basic olivine-rich rock, here classed as a mica-peridotite.

The studies revealed that the widths of coking aureoles were always small, that the metamorphosed zone was usually wider adjacent to larger dikes, but that there was no direct correlation between the size of an intrusive body and the width of the metamorphosed zone.

Chemical and microscopic analyses of the altered coal gave information concerning the nature and degree of metamorphism. By comparing differential thermograms of natural coke samples taken at measured intervals from an 18-inch-thick dike with those obtained from normal coal preheated to known temperatures, cooled, and rerun, estimates were made of temperature to which the coal at various distances from the dike had been heated. At more than 4 to 5 inches from the contact, coal was insufficiently altered to permit estimates by thermal methods, so thin-section studies were used. A maximum temperature of 600° C. adjacent to the dike is indicated, with rapid decrease outward.

INTRODUCTION

Alteration of coal by direct contact with igneous rocks, or as a result of heating by an igneous mass near enough to affect the coal, has been frequently reported. This investigation is concerned with contact metamorphism of coal which has resulted in the production of low-temperature natural coke.

Dikes penetrating coal beds are frequently encountered in underground mining operations in southern Illinois (Cady, 1919). No detailed investigations have been made of them owing to limited accessibility and generally limited exposures.

The uncovering of dikes penetrating the Harrisburg (No. 5) coal during strip-mining operations in Williamson County, Ill., has afforded an unusually good opportunity to study the effects of this type of igneous phenomenon.

Acknowledgments

C. A. Chapman, of the Department of Geology, University of Illinois, gave generously of his time and was especially helpful in determining methods of approaching various aspects of the problem.

Several colleagues at the Illinois State Geological Survey assisted in numerous ways. George M. Wilson and Jack A. Simon aided in field study and collecting of samples, and Mr. Simon helped with the photography. Herbert D. Glass, Clay Resources and Clay Mineral Technology Division, instructed and aided the writer in using differential thermal equipment, assisted in interpreting the thermograms, and critically read that part of the manuscript concerned with differential thermal studies. G. H. Cady and Mr. Simon offered helpful suggestions for improvement and clarification of the manuscript.

LOCATION AND DESCRIPTION OF DIKES

The intrusions are located in the SE ¼ sec. 34, T. 9 S., R. 4 E., near the village of Absher, Williamson County, Ill. (fig. 1). Two prominent exposures are in an abandoned strip mine near the center of the east half of the quarter section; two others are in the highwall which limits the mined-out area about 1,400 feet to the northwest.

At the first-mentioned exposure there are two parallel dikes and at least one minor

apophyseal dike. They strike N. 40° W. and are about 50 feet apart. The smaller dike, to the southwest, is about 18 inches thick at the southeast end of the exposure and increases to 10 feet thick 200 feet to the northwest. The larger dike is 17 feet wide at its northwest end; it is partially covered by rock debris towards the southeast and cannot be measured accurately.

The southeastern limit of dikes that ascended high enough to penetrate the coal bed is about 120 feet from the highwall at the east side of the mined area. There is no evidence of igneous activity in the intervening distance, but rock strata in the highwall show a slight upward bulging and prominent fracturing of the bedrock, indicating that tension fracturing preceded actual intrusion. Further evidence of low pressure at the time of actual intrusion is indicated by the amygdaloidal structure of a small apophyseal dike nearby.

The second exposure is almost in the line of strike about 1,400 feet to the northwest. Here two dikes, badly weathered in the upper portions, are exposed in the 50-foot highwall. They are about 2 feet wide at the base, and divide into small stringers which follow fractures that evidently preceded actual intrusion. Both dikes can be traced to a few feet of the top of the highwall where their upper extremities are truncated and covered by a thin layer of Pleistocene drift. About 125 feet beyond the highwall, an intermittent stream has cut through the drift to bedrock and exposed a section of a dike about a foot thick. The size of the dikes at the highwall indicates that their maximum upward extent was no more than a few feet above their now truncated upper ends. The absence of dikes in strip-mining operations farther to the northwest suggests that the coal there was not intruded.

Pieces of igneous rock are common in the spoil banks between the two principal exposures, suggesting that the exposed dikes are the ends of a single pair of dikes that originally traversed the entire distance.

The time of the intrusion, as determined by local evidence, is post-Middle Pennsylvanian to pre-Middle Pleistocene. It has been suggested however from evidence gained in other parts of southern Illinois that the dikes are post-Paleozoic to pre-Cretaceous (Weller, 1940).

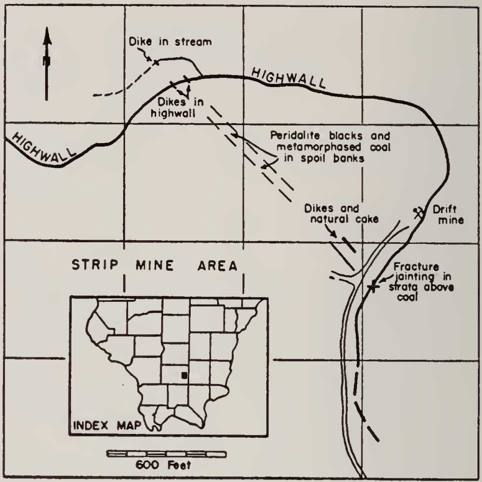

FIG. 1.—Index map of location of the Absher dike area in southern Illinois, and sketch of the strip mine area in SE¼ sec. 34, T. 9 S., R. 4 E., Williamson Co., showing location of igneous intrusives.

DESCRIPTION OF THE DIKE ROCK

The dike rock has a seriate-porphyritic texture. More-or-less equant phenocrysts can be observed. They consist of stubby, doubly terminated euhedra of olivine and pyroxene as much as 1 or 2 mm. in diameter. A few biotite crystals in tablets as large as 10 or 15 mm. across are found along the contacts; olivine and pyroxene phenocrysts sometimes attain a length of 10 mm. These phenocrysts are enclosed in a blue-gray matrix in which grain size is too small to permit identification of individual minerals.

The rock is specular in overall appearance. When the matrix is dark gray to black it tends to mask the phenocrysts and render the rock less obviously porphyritic. When weathered the matrix is lighter, becoming olive greenish; with increased weathering it is light greenish buff to buff with a dull, almost chalky appearance.

Olivine, pyroxene, biotite, pyrite, and calcite are the only minerals macroscopically recognizable. The first three, especially

olivine, constitute the majority of the phenocrysts. Pyrite is scattered sporadically in tiny granular clusters and is more common in weathered rock. Calcite is visible only in the more weathered rock, but effervescence in acid indicates its presence in specimens where it cannot be detected megascopically.

Inclusions of country rock are common only where the contact is essentially horizontal, as along the tops of small sills or where the dike locally terminates against overlying shale. Such inclusions show very little thermal alteration. A few shrinkage fractures, which are generally parallel to vertical contact surfaces, are filled with secondary calcite. They are confined to a zone one or two inches wide along the contact.

The seriate-porphyritic texture and subhedral character of the phenocrysts are more evident in thin sections. A pronounced tendency for phenocrysts to assume a parallel orientation is evident out to 2 or 3 inches from the contact. The change from preferred to random orientation is gradual. Accurate measurement shows that the distribution of large crystals is sporadic and bears no relationship to distance from the contact. The seriate-porphyritic texture persists to the contact with no diminution of average crystal size. No evidence of chilled border zones was observed.

Accessory minerals include apatite, garnet, magnetite, ilmenite, chromite, and perovskite (?). The apatite occurs as tiny euhedral inclusions in larger mineral grains. Garnet also occurs as inclusions but is more common as independent crystals scattered throughout the groundmass. Small garnet crystals form borders around the rims of some altered olivine phenocrysts. Magnetite occurs mostly in fine granular clusters and as irregular individual grains.

Secondary minerals are serpentine, chlorite, magnetite, pyrite, calcite, epidote, and leucoxene. Serpentine, which makes up the greatest portion of secondary minerals, forms a network in olivine and pyroxene crystals and is also associated with these minerals in amorphous form. Magnetite occurs as fine dust, generally associated with serpentine. Pyrite, chlorite, epidote, and calcite are found in minor quantities; pyrite and calcite are more prominent in weathered rock. Small amounts of leucoxene are associated with ilmenite.

The microcrystalline matrix appears to consist mainly of finely shredded biotite, various quantities of chlorite, and some epidote. A cloudy greenish-gray substance, probably an alteration product, commonly masks the groundmass and makes detailed examination difficult. Tiny euhedral and subhedral accessory minerals are sprinkled evenly throughout.

The extensive alteration makes it difficult to name the rock. Serpentinization of olivine and pyroxene has proceeded to the extent that differentiation is often impossible except by crystal form. An intrusive rock of similar composition but coarser texture, recovered from drill cores in the Omaha dome near Omaha, Ill., has been named mica-peridotite (English and Grogan, 1948). On the basis of similarity of composition it is proposed to apply the same name to the rock of the Absher dikes.

METAMORPHISM OF THE COAL

The intruded coal is the Harrisburg (No. 5) bed of the upper Carbondale group of Pennsylvanian age. It is generally flat-lying with slight northward dip and has an average thickness of from 48 to 50 inches. It has the normally bright-banded appearance characteristic of high-volatile bituminous coals of southern Illinois.

Proximate and ultimate chemical analyses of a composite sample, consisting of two channel samples taken from a drift mine about 450 feet from the dikes, indicate the chemical characteristics of coal in its normal condition. Its rank is high-volatile B, in conformity with the A.S.T.M. system of coal classification (table 1).

Physical alteration.—Vesicular coke was formed adjacent to the dikes. The coke gives way quite abruptly to a zone of deformed coal; this grades through a narrow zone into coal that appears to be unaffected, except for abnormal fracturing. The width of the zone of alteration varies, but it is always small; it is generally wider along

Table 1.—Proximate and Ultimate Analyses of the Harrisburg (No. 5) Coal from the Absher Area

	As received %	Moisture free %	Moisture and ash free %	Unit Coal	
				Dry %	Moist %
Proximate analysis:					
Moisture	7.4				8.5
Volatile	33.3	35.9	40.6	39.3	36.1
Fixed carbon	48.6	52.6	59.4	60.7	55.4
Ash	10.7	11.5			
Total	100.0	100.0	100.0	100.0	100.0
Btu per lb.	11,915	12,863	14,535	14,790	13,546
Ultimate analysis:					
Hydrogen	5.34	4.89	5.52		
Carbon	67.43	72.78	82.27		
Nitrogen	1.55	1.67	1.89		
Oxygen	12.33	6.25	7.07		
Sulfur	2.66	2.87	3.25		
Ash	10.69	11.54			
Total	100.00	100.00	100.00		

the larger intrusives. As was also noted by Raistrick and Marshall (1939) for certain areas in the British Isles, no precise relationship appears to exist between the size of the intrusion and the width of the metamorphosed zone.

The progressive alteration from normal coal to natural coke can best be observed as the dike is approached from outside the area of influence. For convenience of description the altered coal may be divided into three zones by the degree of alteration the coal has undergone: (a) outer, or fractured, (b) middle, or deformed, and (c) inner, or coked.

Samples of metamorphosed coal for polished-surface, thin-section, and chemical studies and for differential thermal analysis were taken from a zone adjacent to one of the dikes where the dike was 18 inches thick. The contact here is a vertical surface with a sharply defined boundary separating the dike rock and the natural coke. On the opposite side of the dike, a small sill 10 to 20 inches thick has been injected horizontally about 3 feet into the upper part of the coal bed.

Except for an abnormal amount of fracturing and a slight tendency towards dullness, the coal of the outer zone shows no visible effect of the intrusion. No definite outer limit for this zone can be established because the transition from normal coal to dull, fractured coal is gradual. The fractures were probably developed by disturbance of the coal bed during igneous activity; they are filled with secondary calcite.

As the dike is approached, the character of the coal changes rather abruptly, about 9 inches from the contact, which is the outer limit of the middle zone (pl. 1B). The middle, or deformed, zone is 3 to 4 inches thick. Its outside limit is 8 to 9 inches from the contact and its inside limit 4 or 5 inches from it. The most noticeable feature of the zone is the deformation of the banding, which is inclined upward toward the dike. The general upward trend is modified, however, by minor folds and crenulations which suggest that there was simultaneous upward drag and lateral pressure outward from the dike.

Fracturing of two types is prominent in the middle zone. The larger fractures are interpreted as being tensional and a consequence of drag. They strike parallel with the dike and dip towards it at an angle of about 45°. The smaller, more numerous fractures appear to be dessication cracks, resulting from loss of moisture and vola-

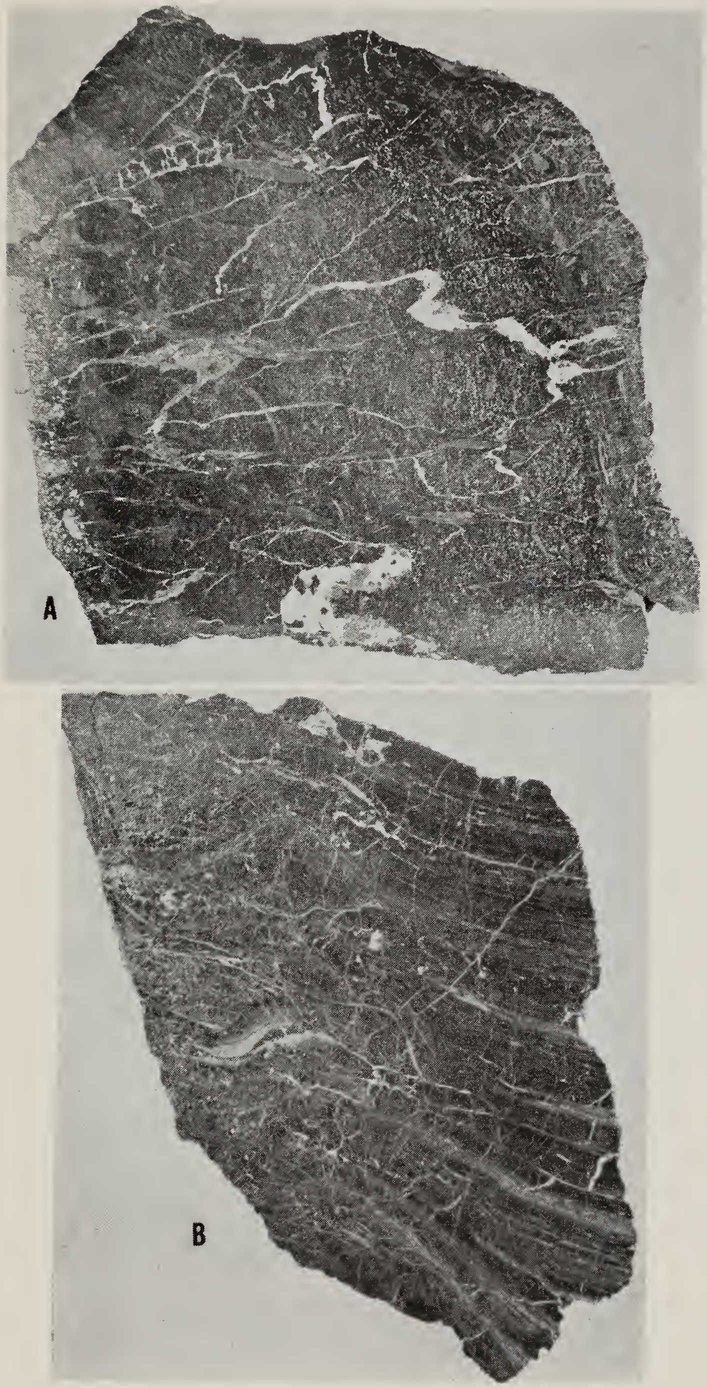

PLATE 1.—Polished surfaces of coal and coke. A. Natural coke adjacent to a mica-peridotite dike 18 inches thick. About natural size. B. Metamorphosed coal from the middle, or deformed, zone along the Absher dike. About natural size.

tile matter when the coal was heated. The quantity of dessication fracturing increases markedly in the direction of the dike. Fractures of both types are filled with secondary calcite and small amounts of quartz.

In normal thin sections, the coal of the middle zone is translucent, but it grades from the typical golden red of bituminous coal to deep brownish red towards the dike. Spore exines, cuticular material, resins, plant-cell structures in vitrain, and yellow waxy bodies are preserved. Except for the resins and waxy material, which are partially disintegrated, they show no effect of heat aside from being deformed and broken and darker towards the inside of the zone.

Vesicularity, barely apparent to the unaided eye, is very conspicuous in thin sections. The degree of vesiculation increases toward the dike. That lateral pressure was greater than vertical is indicated by the flattened form and planar arrangement of the vacuoles. This phenomenon is more easily observed where the coal has completely fused, and is described in connection with the coked zone. The vesicles are filled with calcite and some quartz.

The inner, or coked, zone is 4 to 5 inches wide. It has a well-defined vertical contact surface against the dike and terminates almost abruptly at the middle, or deformed, zone. The coal has been altered to a dull, dark-gray, dense natural coke (pl. 1A). Porosity is easily discernible but the pores are much smaller than those in commercially produced coke. The dull, dark-gray appearance contrasts with the bright, silvery luster of good metallurgical coke. Near the outer boundary of the zone, numerous inclusions of incompletely fused coal are imbedded in the coke groundmass. A narrow zone of inclusions of dike material adjoins the contact.

Fracturing is conspicuous throughout the zone. Large shrinkage cracks are most prominent. They are generally vertical with reference to the normal coal strata and perpendicular to the contact surface. This type of fracturing, at right angles to the heating surface, is characteristic of commercial coke produced in beehive and slot-type ovens, and takes place after the plastic stage has ended. Numerous irregular tension fractures strike parallel to the dike and dip towards the contact wall at about 45°. Their orientation and general appearance indicate that they develop as a result of the upward stress exerted by the dike material, which probably continued to move even after the coking process was well underway.

Polished surfaces were examined microscopically, using oil-immersion lenses and vertical illumination. Thin-section studies were also made. Both the coke groundmass and the incompletely fused coal fragments are opaque. Vesicles contrast sharply with the dark background; they range from 10 to 100 microns, the size appearing to be dependent upon the ease with which the heterogeneous coal material fused when heated. The larger vesicles are not commonly found closer than about one inch from the contact wall.

Characteristically the vacuoles are triaxial elipsoids, except where free expansion has been interfered with by infusible matter such as fusain fragments. They have a planar arrangement with the long axes generally vertical, the intermediate axes horizontal and parallel to the contact surface, and the short axes horizontal and normal to the contact. Their shape and arrangement suggest that during the coking process the direction of greatest pressure was horizontal and outward from the contact surface.

Inclusions of igneous material are scattered in the coke groundmass to a distance of about one centimeter from the contact. They consist of small particles of dike rock that have a microporphyritic texture. Euhedra of altered olivine, pyroxene, and, occasionally, garnet, are also present. No preferred orientation of the euhedra or rock particles is apparent.

Polished surfaces of the coke show traces of the original banding, especially that part of the coke which is more than 2 inches from the contact. The bands are distorted, but a general upward trend points to a dragging movement during the plastic stage. Some of the small shrinkage fractures are filled with coke of extremely fine porosity,

which reflects the differential fusibility of the coal constituents. Fragments of fusian, many of them large enough to be observed megascopically, are imbedded in the coke groundmass. They are usually bent and broken, and may lie in almost any position with regard to the original horizontal layering of the coal. Differential shrinkage of the more plastic coke away from the fusain inclusions has produced small tension fractures, now filled with secondary calcite and small amounts of quartz. The resistance of fusain to softening and melting is indicated by the preserved cell structure and the manner in which the enclosing fusible coal material is bent around the fusain inclusions.

Microscopic fragments of semifusain, transitional between fusain and vitrain, occur throughout the zone. Cell-wall structure is distinctly preserved in the semifusain. No remnants of spore exines or other cuticular material could be detected, even in the outermost part of the zone. Evidence of graphite precipitation, either in the form of crystals or spherules, as described by Stach (1952) for some German natural coke, was not observed.

Intermixing and interflowing of the fused coke mass has not occurred to the extent that it does in artificial high-temperature coke, but extreme distortion of the partially preserved banded ingredients, the random position of the deformed and broken fusain remnants, and the general overall appearance of the coke all indicate that the coal was not subjected to extremes of confining pressure during the coking process.

Chemical alteration.—Proximate analyses are given in table 2. An increase of volatile matter and a corresponding decrease of fixed carbon with progressive distance from the dike would normally be expected. Volatile content does increase, but not gradually. Large increases are shown between samples 1 and 2 and between 2 and 3, followed by smaller increases outward. Five to seven inches from the contact the altered coal still has a higher volatile content than unaltered coal taken from a nearby mine. Fixed carbon decreases outward, but the altered coal 5 to 7 inches from the contact has less fixed carbon than the normal coal.

This anomalous condition can be explained by the character and quantity of ash in the altered coal. Table 3 is a series of analyses of the same samples listed in table 2, but with ash percentages included.

The trend of the ash content, which shows a decrease outward from the contact to a distance of 7 to 9 inches, followed by a progressive increase to a distance of 15 to 17 inches, is largely caused by carbonate-mineral filling of fractures and vesicles. Samples 1 and 2 are representative of the inner zone, which is characterized by large fractures and a high degree of vesiculation. Sample 3 is more typical of the intermediate zone, in which vesicles are very small and deformation was plastic in nature, leaving less vacuole and fracture space to be filled by mineral matter.

Out from the intermediate zone to a distance of at least 17 inches the coal responded to disturbance only by fracturing. Beyond this zone the coal has been mined. The fact that the normal coal contains only 11.5 percent ash, as compared to 23.6 percent for the sample at 15 to 17 inches from the contact, shows that fracturing did decrease outward.

The higher volatile and lower fixed-carbon content of some of the altered coal as compared to normal coal is probably at-

Table 2.—Proximate Analyses, on Moisture- and Ash-Free Basis, of Channel Samples Taken at Measured Intervals from the Contact of an 18-inch-thick Dike

Sample No. / Inches from contact	(1) 0–2½	(2) 2½–5	(3) 5–7	(4) 7–9	(5) 9–11	(6) 11–13	(7) 13–15	(8) 15–17	Normal coal*
Volatile	24.3	31.7	42.7	45.6	47.5	47.8	47.9	50.7	40.6
Fixed carbon	75.7	68.3	57.3	54.4	52.5	52.2	52.1	49.3	59.4

* From the same bed but from a drift mine 450 feet from the dikes.

TABLE 3.—PROXIMATE ANALYSES, ON MOISTURE-FREE BASIS, OF CHANNEL SAMPLES TAKEN AT MEASURED INTERVALS FROM THE CONTACT OF AN 18-INCH-THICK DIKE

Sample No. Inches from contact	(1) 0–2½	(2) 2½–5	(3) 5–7	(4) 7–9	(5) 9–11	(6) 11–13	(7) 13–15	(8) 15–17	Normal coal*
Volatile	17 1	24.1	35.0	38.7	39.7	39.2	39.1	38.8	35.9
Fixed carbon	53 5	52 0	46.8	46.1	43.9	42 9	42.6	37.6	52.6
Ash	29.4	23.9	18.2	15.2	16.4	17.9	18.3	23.6	11.5

* From the same bed but from a drift mine 450 feet from the dikes.

tributable to secondary mineralization. At the temperature at which volatile matter is determined during analysis, the carbonate minerals are dissociated and a considerable quantity of carbon dioxide is formed. Therefore, the volatile content shown does not reflect the "true" volatile content of the coal alone, but consists of "true" volatile plus carbon dioxide from the mineral matter.

DIFFERENTIAL THERMAL ANALYSIS

By differential thermal analysis, using equipment and methods similar to those employed in clay studies (Grim and Rowland, 1944) data was obtained that could be used in determining the approximate temperatures to which the coal had been heated by intrusion. Application of the method to analysis of coal was developed by Glass (1954), who used it in a study of rank in coal.

Samples of natural coke taken at measured distances from the vertical contact face of the 18-inch-thick dike were carefully selected and manually cleaned of as much secondary mineral matter as possible. They were powdered with mortar and pestle, and a 0.5 gm. sample was used for each analysis. A flat nickel cover-plate was placed loosely over the top of the sample holder so that volatile matter could escape. The cover protected the sample from the direct radiated heat of the furnace, and the escaping volatile matter inhibited free entrance of air and thus prevented the burning of the sample. Calcined aluminum oxide was used as the inert comparison medium and was also covered so that both the sample and the inert material would be heated under identical conditions.

Reproducible thermal curves could be consistently obtained for like samples. Samples taken at decreasing distances from the contact produced curves showing volatile matter in diminishing amounts. A series of curves, each representative of coal at known distances from the dike, was thus obtained.

Unaltered coal from the same bed and locality, but far enough from the dikes to be well beyond their zone of influence, was then analyzed as described above. Curves of this normal coal could also be reproduced consistently.

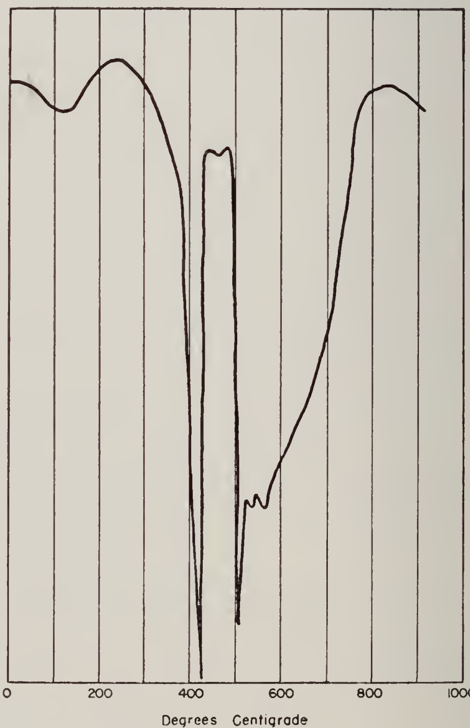

FIG. 2.—Thermogram of unaltered Harrisburg (No. 5) coal from a drift mine in the Absher area.

Figure 2 is a reproduction of the type of thermogram obtained from the unaltered coal. The downward deflections (endotherms) are recordings of endothermic reactions in the sample as it is heated. Exothermic reactions are reflected by upward deflections (exotherms).

The rounded endotherm at about 120° C. is due mainly to moisture loss. The reaction begins below 100° C. and does not reach completion until well above that temperature. Samples were heated at the rate of approximately 10° C. per minute, with the result that nonequilibrium conditions prevailed throughout the entire heating range.

The cause of the exothermic reaction between 200° C. and 300° C. is not known. It may result from partial oxidation of the sample. A short time elapses between dehydration of the sample and the beginning of appreciable evolution of primary volatiles, and during the interval air may enter the sample holder while unopposed by outward-passing gases. Thus a temporary condition favorable to oxidation of the sample would be established.

The low-temperature exotherm is followed by an endotherm that has a pointed apex at about 400° C., which is followed by a sudden upward return. Another pronounced endotherm begins at about 480° C. and quickly attains its maximum downward extent at about 500° C. By this time the plastic stage of the coal has been passed. Greater thermal decomposition takes place in most coals between 500° C. and 600° C., and shortly above 600° C. all tar has been evolved (Brewer, 1945).

Throughout the range from about 300° C. to 500° C., volatile loss is accompanied by softening, swelling, plasticity, fluidity, and resolidification into vesicular char. The thermal curves that develop are a reflection of endothermic and exothermic reactions that take place during the physical and chemical changes. The exact mechanics of the process, as reflected by the thermograms, are not fully understood, however.

Certain observations and inferences can be made by heating samples to various temperatures, quenching them by removal from the furnace, cooling them to room temperature without removing the cover of the sample holder, and then rerunning them. For instance, a sample heated to the apex of the 400° C. endotherm has not swollen enough to lift the cover. If the sample is rerun the 400° C. endotherm is again produced. A sample run to the end of the return from the 400° C. endotherm (about 415° C.) is likewise completely retained within the sample holder, and if rerun, it also gives recurrence of the 400° C. endotherm.

However, when a sample has been heated to the point just before the 500° C. endotherm (about 480° C.), it has the appearance of vesicular coke, or char, and has expanded sufficiently to raise the cover slightly from the sample holder. It is not known whether resolidification occurs at 480° C. if heating is continued without interruption, or whether it takes place near or at the apex of the 500° C. endotherm. Even though the sample can be removed from the furnace in a few seconds, time sufficient for resolidification would most likely have passed. In either event, it has been observed that a state of fluidity and consequent vesicularity has been attained by the time the coal has been heated to 500° C. Samples heated to 480° C. or above do not give a recurrence of the 400° C. endotherm when rerun.

Thermal analyses of coals preheated to various temperatures, quenched, and rerun from room temperature to approximately 900° C. give thermograms which always closely resemble those of natural coke. A diminution of the size of the 600° C. endotherm was observed as preheating temperatures were increased, providing that the preheating temperature was high enough to cause elimination of the 400° C. endotherm when the sample was rerun.

By comparing thermograms of samples of natural coke taken at known distances from the dike with those of normal coal preheated to known temperatures, it is possible to arrive at reasonably accurate approximations of the temperature to which the coal in the bed has been heated by

igneous intrusion. The method cannot be applied to coal samples taken from outside the inner, or coked, zone because the temperature there was not raised enough to cause elimination of the 400° C. endotherm.

Comparisons between thermograms of natural coke and preheated normal coal are shown in figure 3. Thermograms C, D, and E show the effects of contamination by mineral impurities that have prevented normal upward return of the line following the apex of the 600° C. endotherm. The probable normal form of these endotherms, had the completion not been interrupted, is indicated by dotted lines. For comparative purposes, those parts of the three thermograms above about 640° C. have been ignored. This does not detract from the applicability of the method, or lessen its degree of accuracy, because temperature estimates are based on the comparative sizes of the volatile endotherms and the temperatures at which the corresponding reactions occur in the natural coke and the preheated normal coal. The small exotherm between 500° C. and 600° C., which is present in all the thermograms, is caused by contamination of the nickel sample holder with sulfur from the coal. The sharp endotherm above 800° C. in thermograms B, C, D, and E is produced by the calcite that filled vesicles in the natural coke.

Coal preheated to 650° C. (J on figure 3) retained so little of its original volatile matter that the 600° C. endotherm did not return beyond the re-entrant caused by sulfide contamination. It is distinctly smaller than the corresponding endotherms of coal preheated to 600° C. (I) and of natural coke adjacent to the contact (E). The temperature of coal adjacent to the dike apparently was never as high as 650° C.

Volatile endotherms of comparable size are shown in thermograms E and I, indicating that the maximum temperature at the coal-dike contact was about 600° C. By comparison of thermograms D and H, coal from 1 to 2 inches from the contact is estimated to have had a maximum temperature of about 580° C. The endotherm of D extends slightly farther below the sulfide exotherm than it does in H, and it is somewhat broader. Another endothermic reaction at about 650° C. has interrupted the normal return of the line from the apex of the 600° C. endotherm. The relative sizes of the 600° C. endotherms of B and G indicate that the coal 4½ inches from the contact was heated to about 540° C. The sample of B was taken from the outside edge of the coked zone. The endotherm of C is intermediate in size between those of B and D, and a temperature of 560° C. is estimated for the coal 3 to 3½ inches from the dike. Thermogram A shows that the coal 6 to 6½ inches from the contact was never heated to 480° C. because, as previously explained, the 420° C. endotherm does not occur when coal has been preheated to 480° C. (Compare A with F, which was preheated to 480° C.) Sample A was taken from the middle, or deformed, zone.

It was necessary to use thin sections for making temperature estimates for altered coal from outside the coked zone. Investigations to obtain data on the effect of heat on coal have been made by the U.S. Bureau of Mines. Thin sections of coal that had been heated to known temperatures were studied, and the results, with photomicrographs and detailed descriptions, have been published (Thiessen and Sprunk, 1934). By comparing thin sections of the Harrisburg coal from the deformed zone with Thiessen and Sprunk's photomicrographs and descriptions, the temperatures to which the deformed coal had been heated could be estimated. Figure 4 shows the temperatures estimated from thermal analyses and thin-section comparisons, plotted against distance from the dike contact.

DISCUSSION

The question arises as to the rank of the coal at the time of intrusion. The general appearance of the coal at the time of coking seems to have been about the same as it is today. The character of the banding, still preserved in the altered coal, shows that the process of coalification had reached the bituminous stage. The fact that it fused into natural coke when heated by the dike

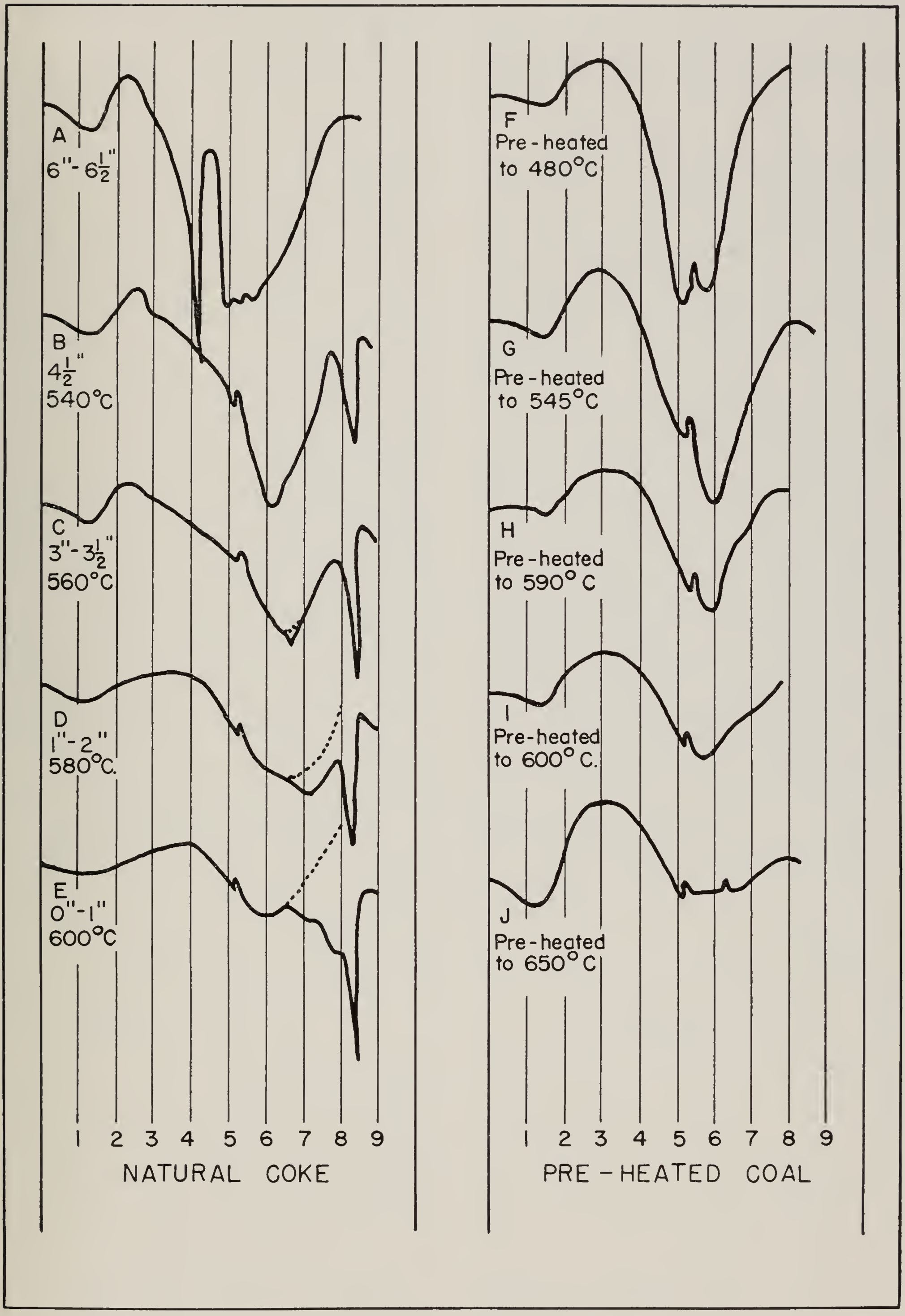

FIG. 3.—Thermograms of natural coke and preheated coal.

is also an indication that its rank was not far below bituminous, because coals of subbituminous rank are nonagglomerating and do not form fused coke. Thus the volatile content of the coal was probably little, if any, greater than it is today.

The above estimates are thought to be the maximum temperatures to which the coal was heated by the intrusion. There is no method of accurately determining how long the coal was held at high temperature. Its rate of cooling would necessarily be largely controlled by the rate of cooling of the dike itself. Drag folding in the middle zone and tension fractures in the middle and inner zones indicate that the dike was active for some time after actual invasion of the coal strata; therefore, there probably was a continuing supply of heat. The dike probably cooled very slowly because of the low conductivity of the country rock.

The coking rate (the rate of advance of the plastic layer away from the heat source) is normally about half an inch an hour. At that rate 9 or 10 hours would have been required for the coked zone to have attained its thickness of 4 to 5 inches. The rate may have been somewhat faster because under natural conditions the coal is essentially monolithic whereas for artificial coking, crushed coal is used.

It seems probable that the coal was maintained at and near maximum temperature for a much greater length of time than were the samples of artificially preheated coal. Volatile matter continued to emanate through the fractured strata and was swept away by the upward-streaming gases from the active dike. Thus it might be inferred that prevailing temperatures could well have been considerably lower than the estimates. The length of time the coal was held at high temperatures undoubtedly was a major factor in determining the quantity of volatiles remaining in the coal after complete cooling.

The effect of pressure resulting from possible deep burial at the time of intrusion must also be considered. Laboratory and commercial coking have demonstrated that nominal pressure is necessary for the production of good coke, and that in some instances good coke can be obtained at lower temperatures if pressures are increased. Within certain limits, the effects of pressure and temperature are complementary (Brewer, 1945).

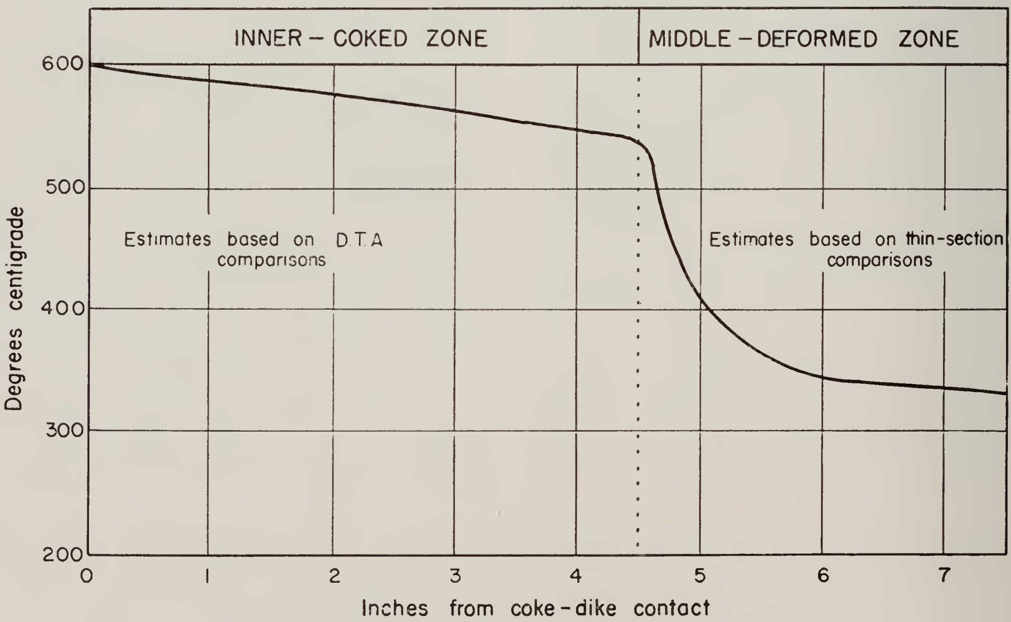

Fig. 4.—Estimated maximum temperature of coal plotted against distance from the dike contact.

Field evidence indicates that pressure was not excessive at the time of igneous activity. The conspicuous jointing above the coal and the dike in the southeast highwall points to a release of pressure as a result of tension-fracturing prior to the advance of the rising igneous material. The manner in which the small dike stringers are controlled by fractures in the country rock also indicates that fracturing had opened avenues in advance. It is difficult to understand how a stringer of material less than one-half inch thick could advance for several feet into country rock unless crevices were already present. An apophyseal dike nearby consists of amygdaloidal rock, showing that, at least locally, confining pressure must have been almost entirely absent. The planar arrangement of vesicles in the natural coke and the manner in which the drag folds of the middle zone are deformed suggest that lateral pressure was greater than vertical.

Even though field evidence indicates intrusion under conditions of nominal pressure, the comparative density of the natural coke and the small size of the vacuoles indicate that normal free expansion of gas during coking must have been inhibited.

Interstitial spaces between coal particles permit considerable expansion when coke is produced in ovens, but the coal adjacent to the dike was not so thoroughly crushed. Fracturing of the coal no doubt took place prior to fusion, as indicated by the broken coal of the middle and outer zones, but it was not crushed as much as coal prepared for the coking oven. It was probably less prone to expansion by virtue of its relatively massive physical state.

Because of the several visible evidences suggesting the absence of excessive pressure, and in view of cited laboratory findings regarding the effects of pressure, pressure is not considered to be of major importance in the Absher area. The temperature estimates are not exact at best and it does not seem likely that greater accuracy can be attained by making adjustments to compensate for the variable effects of pressure.

Although differential thermal analyses indicate that the temperatures were far below those often considered in connection with basic rocks this is not the first investigation which has indicated that such rocks probably are often intruded at temperatures far below those at which they can be melted in the laboratory.

In at least one other study use was made of igneously metamorphosed coal in arriving at temperature estimates of basic intrusive rocks (Sosman, 1938). In that instance, 520° C. ± 30° C. was determined to be the maximum to which coal contained within a basic dike was heated. An estimated temperature of 600° C. for the rock itself was indicated.

Bowen and Tuttle (1949), after investigating the equilibrium in the system MgO-SiO_2-H_2O, concluded that ultramafic rocks could be intruded only in the solid state. Parallel orientation of mineral crystals along the margins of the Absher dikes shows that the rock mass was intruded as a crystalline mush rather than as a molten magma, and the lack of chilled borders is indicative of low temperature. Partial cooling and crystallization of magma tends to produce a "mushy" consistency, and it has been estimated that magma may still be mobile with a crystal content up to 50 percent. Hess (1938) and Turner and Verhoogen (1951) have considered the problem of intrusion temperatures and have given possible explanations of the mechanism involved.

SUMMARY AND CONCLUSIONS

Visual examination of the metamorphosed coal shows that the heat of the intrusive mass produced a dense, finely vesicular coke, similar in structure and chemical composition to artificial low-temperature coke. The coal was heated sufficiently to become plastic or thickly viscous, but the softened mass probably did not interflow to the extent that it does during artificial coking.

Confining pressure during the intrusion was too slight to affect materially the temperature necessary for producing low-temperature coke. Fracturing of the rock strata and coal preceded actual invasion by partially crystalline material that, in the Absher area at least, did not ascend to more than a few tens of feet above the coal bed before cooling rendered it immobile.

Observations indicate that the coal adjacent to the dike attained a maximum temperature of not more than 600° C. and it may have been lower.

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